SUSTAINABLE WOOD STOVES – A VISION

Towards zero emission wood stoves

The SusWoodStoves project consortium

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SusWoodStoves Vision

The SusWoodStoves project

Wood log combustion is important in and for Norway and contributes much to residential space heating and relieves the pressure on the electricity grid and provides energy security when the electricity grid goes down, or when the electricity cost becomes too high. However, wood log combustion contributes also to air pollution, and there is a need to increase the sustainability through stove, building integration and value chain optimization, which has been the main project focus.

The overall objective has been sustainable wood stoves through stove, building integration and value chain optimisation.

The sub-objectives have been:
1) Speciation and quantification of particulate and gaseous emission levels from wood stoves for representative stove technologies and operating conditions,
2) Reduction of climate and health related emission levels through emission reduction and energy efficiency measures,
3) Optimum building integration of stoves,
4) Assessment of value chain performance of existing and improved stove technologies and connected systems for different stove-building configurations in Norway,
5) Techno- and socio-economic assessments of the current and future role of wood stoves in the Norwegian energy market,
6) Development of a roadmap for sustainable wood stoves in Norway,
7) Education of highly skilled candidates within this area and training of industry partners,
8) Monitoring of activities and state-of-the-art within this area and dissemination of knowledge to the industry partners, and other interested parties when applicable.

The first step of the roadmap development was to develop a vision for the further development of wood stoves as a key renewable space heating technology and contributor and energy security provider towards 2050.

THE HISTORY AND IMPORTANCE OF RESIDENTIAL WOOD COMBUSTION (RWC) IN NORWAY

Residential wood combustion (RWC) has been a cornerstone of Norwegian life for centuries, deeply woven into the fabric of the nation's history and culture. This practice, which involves burning wood for heating and cooking, has not only provided warmth and sustenance but also a sense of comfort and tradition that resonates with many Norwegians.

Imagine the early Norwegian settlers, braving the harsh Nordic winters with little more than the warmth of a wood fire. For these early inhabitants, wood was not just a fuel; it was a lifeline. The dense forests of Norway provided an abundant supply of firewood, which became essential for heating homes and cooking food. Traditional Norwegian homes, especially in rural areas, were built around the hearth, where families would gather to share stories and meals, creating a sense of community and belonging. The development of more efficient wood stoves and the introduction of chimneys made wood burning safer and more effective.

It was in the Middle Ages that people started burning wood in open fireplaces with chimneys, to heat their houses. However, the efficiency of these fireplaces was horrible, only around 20-30 % [1]. Closed iron stoves were produced in Norway from the beginning of the 17th century and gradually replaced the open hearth, smoke stoves and fireplaces. Stoves for firing with wood or coke arrived on the market after 1850. Coke, a by-product of coal-based gas production, was introduced as an affordable and efficient fuel in homes. Kerosene stoves were also used. Due to extensive overuse of wood for heating purposes in Scandinavia, as well as other competing uses of wood, like ship construction, new stoves with much better efficiencies were "invented". The so-called tiled stoves were then first introduced into the Swedish market,

AKTIESELSKAPET JØTUL — OSLO

1927

Automatisk regulering av magasinovner.

En epokegjørende opfindelse.

Den trækregulator, som nedenfor er beskrevet, vil efter vor mening

spare mindst 20 % i brændsel,

og hvad betyr saa ikke dette nationaløkonomisk? Besparelsen løper op i millioner.

Og vi mener at regulatoren vil

spare 80 % i betjening,

Adolf Wilhelm Josef Watzinger (born 10 June 1879 in Darmstadt in the Grand Duchy of Hesse in the German Empire, died 13 September 1959 in Trondheim, Norway). He was a mechanical engineer, dr.ing. 1909, educated at the college in Darmstadt and at the University of Geneva. He was appointed as a professor of machine learning at the Norwegian Technical University in 1909 as the very first professor at the university.

https://media.digitalar-kivet.no/view/191197/5

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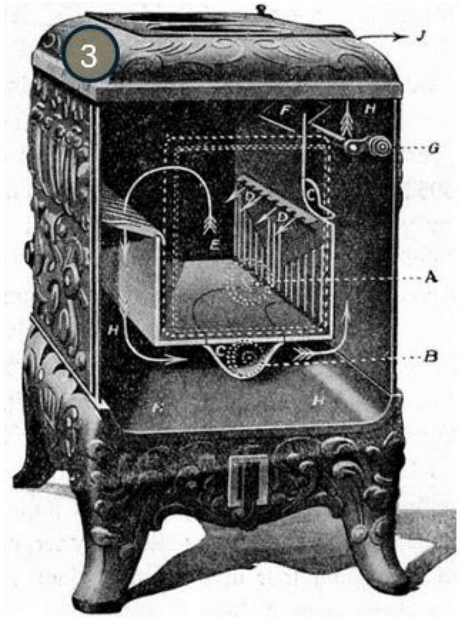
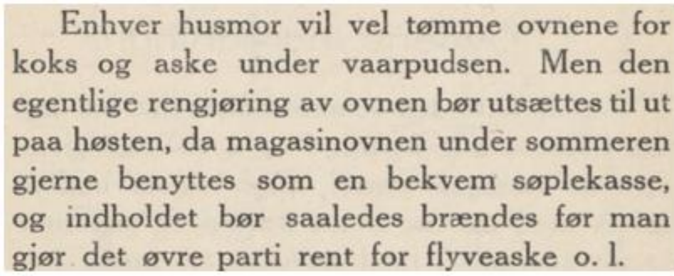
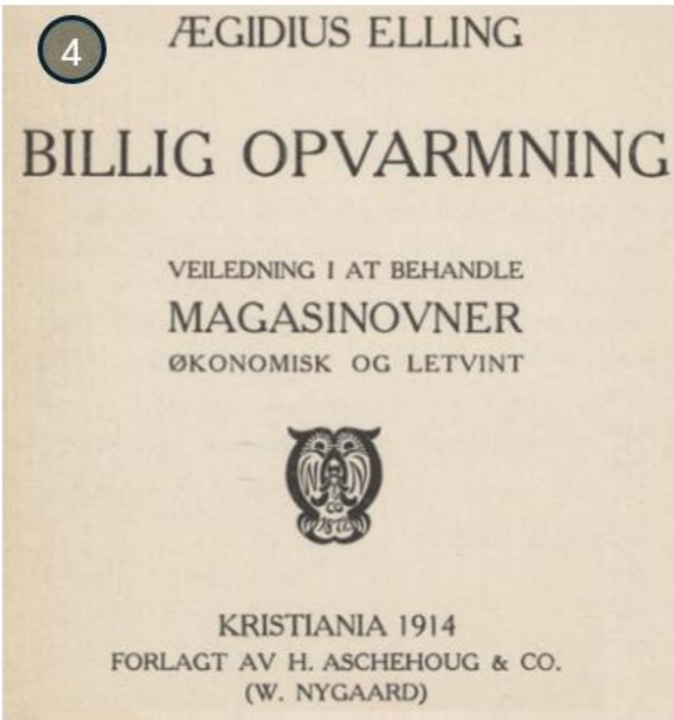
applying flue channels through masonry, achieving very good heat exchange from the flue gases and efficiencies above 90 %. The Swedes probably picked up the idea from Germany, where such stoves had existed since the 15th century. Here at home, more and more ironworks appeared which supplied cast iron stoves on a large scale.



Even at the turn of the 20th century, people in general were concerned about the cost of heating their homes. The most typical stove in those days was the “all-burning” coke stove (“magasin/sylinderovn”), which was filled up with coke and then ignited at the top. It would burn all night. Usually, it was the responsibility of the women to keep the fire alive, and not only just one, but almost one in each room. Then it was not surprising that someone, namely Prof. Adolf Watzinger at NTH (Norges Tekniske Høgskole) invented an automated stove as far back as 1927, to ease their work [2, figure]. Nobody cared about emissions then, but rather the efficiency and the ease of operation. The automated stove could burn for more than 24 hours without intervention. Another invention in the early 20th century was the use of secondary preheated combustion air as in Bjørnovnen from Drammen ironworks [3, figure], though still missing the insulated combustion chamber.



Enhver husmor vil vel tømme ovnene for koks og aske under vaarpudsen. Men den egentlige rengjøring av ovnen bør utsættes til ut paa høsten, da magasinovnen under sommeren gjerne benyttes som en bekvem søplekasse, og indholdet bør saaledes brændes før man gjør det øvre parti rent for flyveaske o. l.



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ÆGIDIUS ELLING

BILLIG OPVARMNING

VEILEDNING I AT BEHANDLE

MAGASINOVNER

ØKONOMISK OG LETVINT

KRISTIANIA 1914

FORLAGT AV H. ASCHEHOUG & CO.

(W. NYGAARD)

Some of the first user-instruction manuals appeared around 1914, including maintenance guidelines [4, figure]. Eventually, it became common to build what was referred to as “The poor man’s tiled stove”, meaning cast iron stoves with several additional sections above the combustion chamber to enable the passage of the flue gases for better efficiencies. Many of these stoves became icons, designed by famous Norwegian architects and artists. However, much of the artfulness disappeared after the 2nd world war, when the country had to be rebuilt. Ordinary people had little money and wanted cheap stoves, and cheap stoves we gave them. Many of the stoves produced between 1940 and up to the 1990'ies, are still alive and responsible for a large portion of the emissions we have today.

After the 2nd world war, the mid-20th century brought significant changes to Norway, with economic growth and urbanization leading to new heating methods. Imported coke was becoming increasingly more expensive and was eventually exchanged for wood, and then people had to be educated on how to use their stoves with this "new fuel" [5, figure].

In the 60'ies, electricity and oil began to replace wood in many urban homes. Then the oil crises of the 1970s reignited interest in wood as a renewable energy source, prompting advancements in wood stove technology and government support for sustainable energy practices. In the 80'ies, design was reintroduced as an important sales pitch again. Suddenly people wanted to admire the flames, thus the introduction of larger and larger glass areas surrounding the combustion chamber.

Beyond its practical uses, wood combustion holds a special place in Norwegian culture. The sight and smell of a wood fire evoke a sense of coziness and tradition, often referred to as “hygge” in Scandinavian culture. Wood burning is also associated with cherished outdoor activities like cabin stays and bonfires, which are integral to Norwegian leisure and social life. These moments around a fire, whether indoors or out in nature, foster a deep connection to the land and to each other. Residential wood combustion in Norway is more than just a method of heating; it is a tradition that has adapted over time to meet modern needs and environmental standards. While it poses challenges in terms of air quality, ongoing advancements in technology and regulations aim to mitigate these issues. The cultural and economic importance of RWC ensures that it will continue to be a cherished part of Norwegian life, providing warmth, comfort, and a sense of connection to the past and to each other.

THE PERFORMANCE HISTORY AND CURRENT TECHNOLOGICAL STATUS OF RWC IN NORWAY

Today, modern wood stoves have combustion efficiencies between 75-90 %, and almost no emission of particles in “contrast” to old wood stoves. Then again old wood stoves (1940-1998) had quite low efficiencies and high emissions compared to some of the best antique ones (including tiled stoves), which among the best ones, often were almost equal in emissions and efficiency compared to the average modern stove since 1998. The real oldies from the 16th century had efficiencies between 20-30 %.

In the past you could only get a wood-burning stove in either grey or black, but now you can get wood-burning stoves in many different colours built with alternative materials. On the market today, you find everything from traditional cast iron stoves, re-engineered for low emission and high efficiency, to hyper stylish designer stoves and stoves where the combustion chamber is entirely surrounded by glass. “New” concepts have also been introduced on the market, like the two-chamber downdraft solution, with a performance equal to a typical pellet stove. Fun-fact is that the oldest patent for a downdraft stove is from 1869.

Today, many new houses are built with hydronic (i.e. water-based) heating. More and more people choose to connect a wood-burning stove to this water-heating system, some also adding solar vacuum tubes into the circuit. If you have access to affordable firewood, the house's heating costs can be greatly reduced, while you can enjoy the cosiness of a fireplace at the same time.

Today, the best wood stoves outperform the staged air combustion wood stoves introduced in the 1990s, due to continuous engineering improvements as well as new and improved designs. The new wood stoves of today are performing much better than an average new stove representing all wood stoves produced from 1998. PM emissions have been reduced by more than 50 %. CO, NMVOC, organic carbon in PM and CH4 with 70-75 %. In the future we will need to see further reduction of all emissions, especially for the smallest particles. What remains the biggest challenge are emissions of black carbon (BC) particles and NOx.

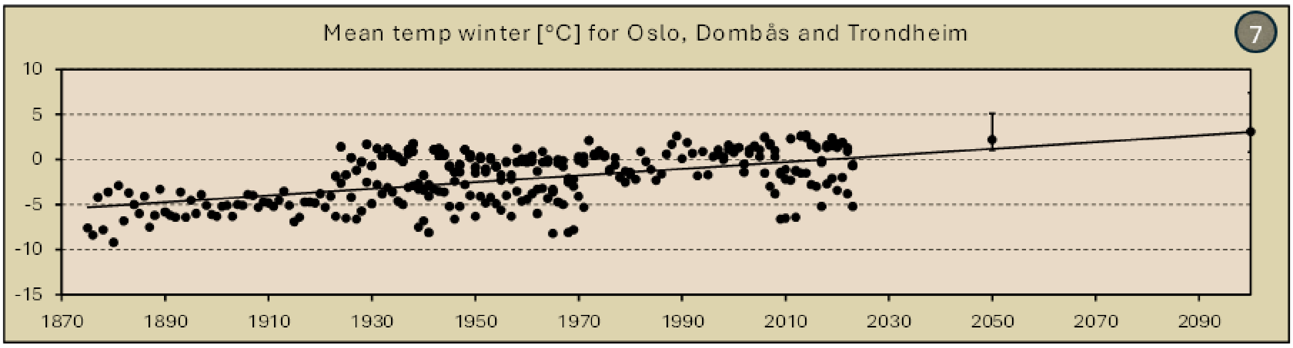
THE FUTURE OF RWC TECHNOLOGY AND SYSTEMS - IMPROVEMENT POTENTIALS AND NEEDS

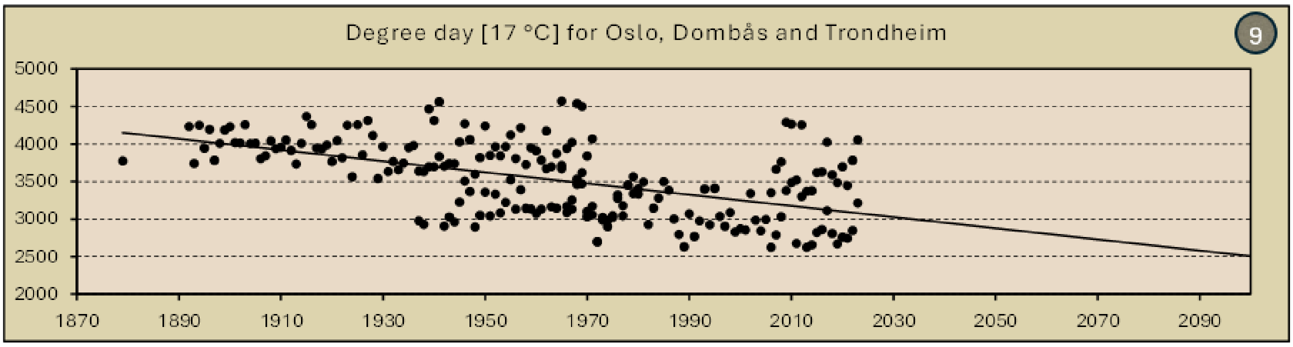
RWC is at any given moment linked to the cost of electricity, the outdoor temperature, the cost and availability of firewood and regarding investment - the cost of a stove compared to competing technologies. In the longer run a continued acceptance that CO_2 emissions from burning biomass are carbon neutral and social acceptance is needed. From a building perspective, how well insulated modern buildings will be and how well the heat from a point source can be distributed is important. From an emissions and energy performance perspective, how fast the old stoves can be replaced with new clean-burning ones and how fast innovations and technological advancements can reduce the remaining harmful emissions and raise the energy performance is important.
The first goal to be achieved is to raise the wood stove performance to that of pellet stoves, both in terms of emissions and efficiency. The ultimate goal would then be net zero emissions as of 2050, and pursuit of efforts to pave the road for achieving carbon negative wood stove systems through technological innovation and promotion of advanced forest management strategies.

NOU 2023:3 claims that more renewable power in the future will result in larger price variations, more like we have seen in recent years. Towards 2050, it is expected that a greater proportion of the power production will be flexible. NVE estimated in its long-term power market analysis (2021) that prices up to 2040 will be significantly higher than the average of the previous 20 years. Greater seasonal price fluctuations are also expected in Norway, with energy prices being much higher in winter, as the whole of Europe’s energy mix becomes more weather dependent. Small-scale room heaters are not mentioned specifically in Energi21, however, in NOU 2023:3, such solutions are held open for consideration. It is stated that “The importance of bioenergy as a flexible energy resource in a future where the cost of electricity increasingly varies must be further analyzed.”

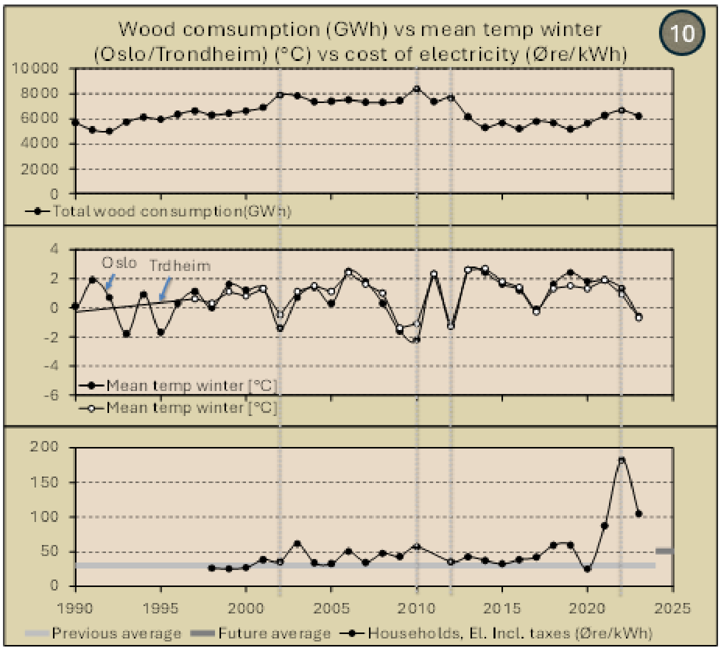
Today, Norway is dependent on wood burning so that the power grid can withstand the demand on the coldest winter days. In Norway, something in excess of 25 TWh of electricity is used only for heating residential buildings. An additional 6-7 TWh is covered by wood (and pellets) and 2 TWh by district heating. If the results from the THEMA mapping [6] can convince politicians that this is a climate-friendly and sustainable solution, the use of wood for space heating would possibly see a renaissance and a long-term bright future!

Then again there is the weather, global warming and the increasing use of renewable energy sources with their weather and season dependent production. A plot of the average winter temperature in Oslo, Dombås and Trondheim [7, figure] shows to be steadily increasing towards 2.2 and 3.1 °C in 2050 and 2100. These are for a medium emission scenario [8]. A high scenario predicts an average winter temperature in 2050 and 2100 of 2.7 -0.4/+0.8 and 5.2 -0.9/+1.5. Analysing the degree day evolution [9, figure] shows the same pattern, with a steady decrease towards 2050-2100. Increasing winter temperatures of course means less need for space heating, however, wood stoves play a role in mitigating risks from extremes, increasing the resilience of the whole electricity system.





If we compare firewood consumption (GWh), electricity price (øre/kWh) and the average winter temperatures since 1990 and up until today, we clearly see this typical winter temperature-dependency for both wood consumption and electricity price [10, figure]. This results in an unpredictable and unstable market and makes foreseeing future trends difficult.



Recent data shows a clear link between the electricity price in southern Norway and weather conditions leading to no wind power in neighbouring countries, a situation which is amplified by dry periods. National electricity grids are becoming increasingly linked to international grids and influenced by international events, which at times leads to very high electricity prices. Then heating with firewood becomes a very economical option for many. If something can be taken as a lesson from this, it might be… “Que Sera, Sera, Whatever will be, will be, The future's not ours, to see” and that the wood stove industry must be on the tip of their toes every year, able to readjust production and inventory in less than a year’s notice, while also preparing for the future.

THE 10 POINT VISION:

1. Contribution to renewable heat provision and fossil fuels displacement - Why renewable heat from wood stoves are actually needed also in the future and how it can beneficially be combined with other energy sources, and why wood stoves have a role to play to contribute to the overall displacement of fossil fuels

Renewable heat, and electricity, provision is the key to displace fossil fuels and abate global warming. The impacts of fossil fuels on global warming are not a national challenge, and a global effort is needed. Biomass has traditionally been dominating the renewable heat provision [11]. But times are changing, and with the introduction of heat pumps, the argument that electricity should be reserved for carrying out work and not heating is weakened. Today the arguments for needing heat provision by combustion of wood logs in wood stoves should rather be connected to biomass being part of the renewable energy system, and as long as we don't produce, by far, enough renewable energy, all renewable energy sources are needed to displace the fossil fuels. Wood stoves hand in hand with heat pumps makes (a lot of) sense from an energy perspective, and a heating power perspective.

Today, we don't have enough renewable energy, but in 2050? Are wood stoves really needed in the future from a pure renewable energy perspective? Is it realistic with increased use of wood stoves? Doubling, and more regarding energy actually utilised? Should we defend wood stoves from a totality perspective (energy security, hygge…), not only energy? The answer to these questions is yes, wood stoves are needed due to their unique position and features.

Modern wood stoves are clean-burning and energy effective, and very suited to provide affordable space heating and energy security. Wood stove technologies and systems are continuously improving and will therefore also in 2050 be a preferred space heating technology.

No fossil fuels allowed in the future? This is not necessarily true, as negative emission solutions are being developed. It is in principle about using our resources in the most efficient way so that we achieve the greatest benefits, sustainably, globally. For biomass resources the question is how we can utilise them in the best way to maximise energy provision while at the same time covering higher purpose (e.g. materials) needs.

Substituting fossils fuels is an argument today, but will it be in the future? (a future where fossil fuels are almost history regarding energy production, and where carbon capture and storage (CCS) is commercially applied, also partly for bioenergy). Biomass is also needed to displace fossil materials in addition to other material applications, and maybe this needs priority in the future?

Bioenergy will still be important in 2050, including for space heating. While biomass will also be needed for material applications, there will still be large amounts of residual biomass, including firewood, available for energy purposes. Use of fossil resources for material and partly energy applications will still be an option in 2050, as CCS will provide the option to still become a net zero-emission society.

2. Contribution to energy security - Why wood stoves are needed in the future from an energy security perspective

Energy security is becoming more and more important, due to unrest, but also due to more extreme weather conditions caused by global warming. Wood stoves operate without the need for electricity, or electricity can be supplied from a battery or even the generated heat itself if the stove is operating with automation of the air supply. But buildings are becoming increasingly energy efficient and different types of heat storages and battery solutions are developed to supply heat on demand. However, the renovation rate for older buildings is still relatively slow, meaning that many moderately insulated buildings will still exist in 2050 [12].

Today wood stoves have a clear benefit regarding energy security (about 2.5 million wood log fired units are installed in Norway, representing a net heating effect of about 15 GW). In the future, reduced heating needs in buildings and other means of providing short term heat will reduce that benefit. Energy security is also coupled to costs, i.e. if the electricity becomes so expensive that people cannot afford using it for heating purposes. Will only extreme situations, as extreme weather conditions or a war, leading to electricity grid blackout, be the valid energy security argument in the future?

Electricity grids and components are and never will be perfect, meaning that electricity outages will happen also outside extreme situations. For individuals, having a heating technology that works independently of grid electricity is very valuable, and wood logs are an economical alternative to electricity for many, especially in cold weather periods. The features of a wood stove complement e.g. a heat pump well, making this system a flexible, economical and secure space heating system.

3. Relieving the electricity grid - How and to which extent wood stoves can contribute to relieve the pressure on the electricity grid until 2050

Electricity demand will increase, while the electricity grid has capacity challenges. It is costly to expand and strengthen the electricity grid in Norway, and it takes time. New electricity consuming technologies are expanding which pressures the electricity grid, and some companies cannot even establish themselves in Norway due to lack of available (contract) electricity. Especially wind turbine-based electricity is fluctuating (intermittent), and land-based wind turbines create controversies. Solar energy is also intermittent and is not there when you need the heat or the electricity the most. Hydropower is sensitive to water availability and there is increasing evidence of recent curtailments of hydropower production as a result of drought events, which are predicted to become more intense and frequent under ongoing climate change. A combination of drought (less hydropower) and no wind can have drastic influence on electricity availability and prices. E-fuels made with excess electricity from non-storable renewable energy have a future potential as well as batteries and new and improved battery technologies. Even nuclear power has come up again as a solution to cover our electricity needs. Norway is part of the European electricity market, which is positive, but it can also be challenging.

The electricity grid capacity challenges today occur at certain times, but for most of the time not. The good thing for wood stoves is that it coincides with the periods with high heating demand and hence also high electricity demand, and often high electricity cost. Will that be the case in 2050, with more energy efficient buildings, more heat pumps, more (locally) produced electricity, more heat/electricity storage, and a strengthened electricity grid?

The demand for electricity and electric effect will not stagnate as the society transforms towards a net zero-emission society. Expansion and strengthening of the electricity grid will have continuous focus, so non-electricity space heating technologies will be important to relieve the pressure on the electricity grid. Here wood stoves have a key role to play, as they can provide a high heating effect when needed on the coldest winter days, when the demand for electricity and its price are at its highest. We will see increased integration and improved utilisation of all energy sources in the overall energy system in the future.

4. Contribution to value creation nationally and internationally - How we can increase value creation by increased technology development and implementation in a national and international market

High performance and quality Norwegian technology has a great potential to be implemented nationally and internationally, contributing to increased value creation, export and market shares. However, substantial research and development are needed to decrease emissions to in the end reach a zero-emission target.

This zero-emission wood stove system (modular and flexible) could contribute to considerable value creation both nationally and internationally. Is it possible to achieve this without international cooperation? Probably not. Is it possible to achieve this without a financial and strategic support from authorities? Probably not. How do we create the needed momentum (economical, political, social) to reach a zero-emission target for wood stoves?

Research and development are needed in all areas to enable reaching a net zero-emission society in 2050. While modern wood stoves today are considered clean-burning, still they have the potential to reach significantly lower emission levels. By adding secondary technologies and seeing the wood stove as part of a heating system, further optimisation and emission reduction are possible, enabling in the end to reach zero emissions. This should be done as an international joint effort and with necessary political and economic support, as for other renewable energy technologies. The connected value creation potential connected to this will be substantial.

5. Caretaking socio-economic aspects - Why wood stoves are a future recommended technology based on its socio-economic benefits

Using wood stoves for domestic heating has a long history and deep social roots, and many have access to own or affordable firewood. Domestic heating with wood logs then becomes an economic heating choice for many. Even for those that don’t have access to own/cheap firewood, heating with wood logs can be economical when the demand for electricity is high and the cost of it is correspondingly high. From a national economic point of view there are more factors to consider, including jobs creation and value creation, to be balanced with positive and negative effects of the energy provision through entire value chains, as for all renewable energy technologies.

Wood stoves, if allowed by authorities, will they always be there since many have access to free or affordable wood logs? At certain times, will heating with wood logs always be cheaper than with electricity? From a socio-economic point of view, we will probably for the foreseeable future need wood stoves. From a national economic point of view, do we really need wood stoves?

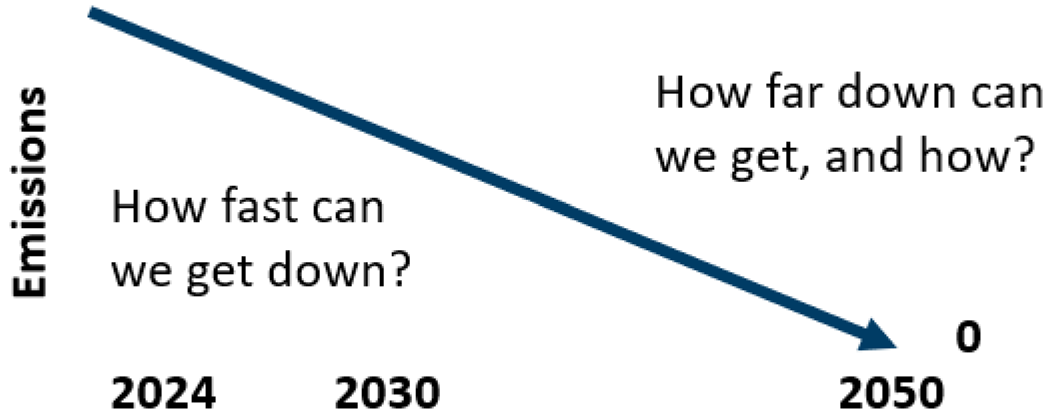
Wood stoves, through their features and complementarity to electricity-based heating, will always be needed and wanted from a socio-economic point of view and have advantages from a national economic point of view. Modern wood stoves are clean-burning and the technologies are continuously improving. Modern wood stoves therefore have an important role to play from a socio-economic point of view.

6. Emissions reduction and reduced negative impacts - How we can further develop wood stoves and their connected system to secure low emission levels, also in real-life and point towards needs for improvements when assessing the effects of emissions from wood stoves

The sustainability of wood stoves is influenced by several factors, mainly as the emissions from wood stoves results in impacts on environment, climate and health. The impact on health is primarily as a contribution to the overall air pollution, where recommended limit values exist for the concentration of several pollutants in the ambient air. Large uncertainty is connected to establishment of direct health impacts of the individual emission sources, related to concentrations, compositions, sizes and combined effects – coupled to several health issues having varying effects on different parts of the population. The modern wood stoves of today have much reduced emissions due to technology advancement, a fact, but emissions are still influenced by other factors, connected to fuel quality, operation of the stove, and the building and its chimney.

Human awareness and willingness are keys to achieve the low emission levels made possible by technology development. Automation is key to relieve the user of some of the operator responsibility, but there is a limit to what can be automated, and there is a limit to how good or intelligent the control system can become. A human versus technology balance must be found. Type approval test standards for wood stoves are not mirroring the real use of a wood stove, and it is well known that accredited test institutes know how to achieve very low emission levels, which cannot be matched by a normal user. Also, the wood stove is not a standalone unit, it is part of a system and a building that also influences its performance.

Are zero emissions possible? Within 2050? And real-life emissions? Zero harmful emissions? Zero harmful emissions of unburnt? Is (increased) differentiation between different emission components needed? Will automatic stoves take over? Will they be good enough? Should we rely also on secondary measures? (catalyst(s), electrostatic precipitator (ESP)). Should type approval tests change? Should stove build quality improve? (as poor build quality results in leakage air). Should a “driver license” be required to be allowed to operate a wood stove? Is a real-life emission monitoring system needed? Or real-life testing?



Several factors are influencing emission levels, and for wood stoves the human factor is also important. By focusing on innovations, technology development, automation and education and user training real-life emissions can also reach very low levels. In parallel there must be a continuous focus on increasing the knowledge and database on the actual impact of individual energy technologies and emission compounds on human health.

7. Increased safety - How we can make sure safety is caretaken during wood stove operation and minimise safety risks

Wood stoves are operated by humans and are not independent of the house and the chimney. A result is that many chimney fires takes place every year, in the worst case burning down houses and causing human casualties.

Chimney fires are a serious challenge. Today continuous monitoring of the chimney condition (temperature) is possible, to prevent chimney fires. However, if zero-emission, and robust, wood stoves are the target, will continuous monitoring be needed in the future? Or should it be expanded to also include emission monitoring, the use of artificial intelligence, and with feedback to the user, and others?

Modern wood stoves when installed correctly and operated as intended are safe to use. Monitoring of the wood stove operation and the chimney condition and the use of artificial intelligence have the potential to provide the user and others with information that is useful for improving the operation and caretaking safety.

8. The importance of technology development and replacement - How we can accelerate the replacement in the existing building stock, even of the oldest new technology, and estimate how much would this contribute to reduced emissions and impacts (real-life) towards 2050

Technology advances continuously, in all technological areas. SusWoodStoves has clearly shown how that impact emission levels [13]. Positive effects of replacing old/poor technology are obvious but assessing how big these effects are is not straightforward. A continuous focus on acquiring quality data needed for decision making by authorities is needed.

When should all old wood stoves be replaced, within 2050? Should all "old" modern wood stoves also be replaced within 2050? No stoves from before 2020, or 2030, in 2050? Should in the near future (2030?) new houses be equipped with a zero-emission wood stove system? Should older houses upgrade their system, making sure that the chimney fits the new modern stove, and should they also install an ESP?

All old wood stoves should be replaced by modern clean-burning ones, as they have no place in a net zero-emission society. As modern woodstoves are continuously improved, also replacement of old modern wood stoves is natural and needed. These new modern wood stoves must fit the building and its chimney, covering the heat need in an optimum way. To reach a net zero-emission society in 2050, the new modern wood stoves and/or the chimney must also incorporate secondary emission reducing technology, and the operator must be educated to operate the system optimally.

9. Contribution to biodiversity - Why biodiversity impacts resulting from procurement of trees for making wood logs are low and how they can be further minimised

Biodiversity impacts have come up as a key argument against increased use of biomass. In principle the use of wood for energy should be based on wood residues from forest- and wood processing industry, and other smaller sources. Wood logs should not be produced from trees that could serve a higher purpose, and not only from one wood specie (e.g. birch), but from a wider selection of wood species. However, some wood species are better equipped to adapt to the effects of global warming. In Norway, most of the wood used in stoves currently comes from birch. Birch forests are typically characterized by better habitat conditions than spruce and pine, which are currently the most common species in Scandinavian forests. Wood stoves trigger demand of birch, whose expansion over coniferous species is typically indicated as a promising strategy to support wood supply and improve many indicators connected to biodiversity and ecosystem services. Birch is also among the most suitable fast-growing species that can naturally encroach onto marginal land and abandoned cropland, and securing market demand for birch can increase opportunities for large-scale revegetation and more sustainable resource supply.

There are or should always be a higher purpose (higher than energy provision) for extensive/intensive harvesting of forest resources. Sustainable forest management is a prerequisite, including minimising biodiversity impacts. In the SusWoodStoves project we have shown that softwoods also are well suited as wood logs [14]. Hence, more residual softwood (e.g. spruce, pine) could be used, instead of only about 20% used today in Norway, the rest being mostly birch. Decreased environmental and climate impacts of wood stove use should contribute to less biodiversity impacts. Non-sustainable harvesting of trees to be used for wood logs must be avoided.

The wood resources used for making wood logs (firewood) are not high quality resources that naturally would go to higher value purposes. As such firewood is a residual wood resource with minimal biodiversity impacts if sustainably harvested from the whole range of residual firewood sources. Further expanding demand for birch wood can also stimulate more biodiversity-friendly forest management strategies.

10. Preserving the hygge - Why wood stoves are important from the hygge perspective, and how the hygge factor can be maintained and possibly improved while the wood stoves are improved regarding performance and user friendliness and -robustness

Can anything replace wood logs when it comes to hygge? The heat radiation? The flame picture? The sound? The feeling? Not really, not even other wood-based heating technologies.

Nothing can replace the hygge factor wood stoves are creating, which also could make wood stoves challenging from an emission and energy efficiency point of view. However, modern wood stoves have maintained and enhanced the hygge effect while considerably and continuously reducing emissions and increasing the energy efficiency. Pellet stoves are the natural emission and energy efficiency benchmark, but what about hygge then? Without preserving the hygge factor, how many will use wood stoves in the end?

Wood stoves are a space heating technology and a key hygge provider in peoples living rooms. This is socially very important, and the hygge effect is not reduced with modern wood stoves, but increased.

CONCLUDING REMARKS

This Vision lays the foundation for a Roadmap for the further development of wood stoves as a key renewable space heating technology and contributor and energy security provider towards 2050. To reach this goal research-based innovation is needed in several areas, paving the way towards zero emission wood stoves.

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